The Zero Boil-Off Tank (ZBOT) Experiment Role in Development of Cryogenic Fluid Storage and Transfer Technologies

Dr. David Chato
NASA/GRC

Dr. Mo Kassemi
NCSER

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ZBOT Project Team

Glenn Research Center

SCIENCE AND MANAGEMENT

Bill Sheredy– NASA GRC PM
Mohammad Kassemi – PI, NCSER
David Chato - Co-Principal Investigator, NASA
David Plachta – Project Scientist, NASA
Sonya Hylton – Research Scientist, NCSER
Olga Kartuzova – Research Scientist
Bart Gruber – Project Lead, ZIN

ENGINEERING

Bernie Bolte – Electrical Engineer, ZIN
Robert Brock – Software Lead, ZIN
Jim Bruewer – Manufacturing Manager, ZIN
Tony Bruzas – Chemical Engineer, ZIN
Kimesha Calaway – Systems/Integration, ZIN
Kevin Dendorfer – Electrical Technician, ZIN
Jeff Eggers – Software Engineer, ZIN
Jeff Fortuna – Mechanical Designer, ZIN
Greg Funk – Systems/Integration, ZIN
Andrew Kawecki – Mechanical Technician, ZIN
Alex Kieckhafer – Thermal Engineer, ZIN
Chris Lant – Optics, ZIN
Kevin Magee – Fluids Engineer, ZIN
John Morrison – Software Engineer
Jim Ogrin – Mechanical Lead, ZIN
William Pachinger – Electrical Engineer, ZIN
Jim Paskert – Manufacturing Engineer, ZIN
Rick Pfeiffer – Electrical Designer, ZIN
Joseph Samrani – Electrical Lead, ZIN
Craig Totman – Mechanical Engineer, ZIN
Chris Werner – Structural Engineer, ZIN

SAFETY and MISSION ASSURANCE

Alex Beltram– RM Facilitator, ZIN
Brian Loucks– Quality Oversight, ARES
Nechelle Grant - Risk Management, ARES
Rick Plastow– Software QA, Bastion
Chris Bodzioney– Safety Engineer, ZIN
Darryl Seeley – Quality Assurance, ZIN

Background and Motivation

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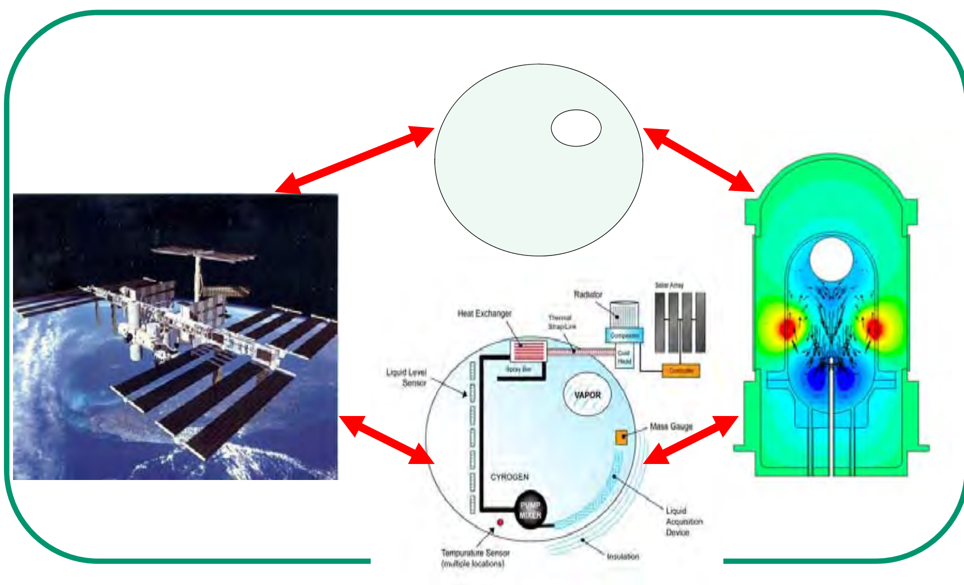
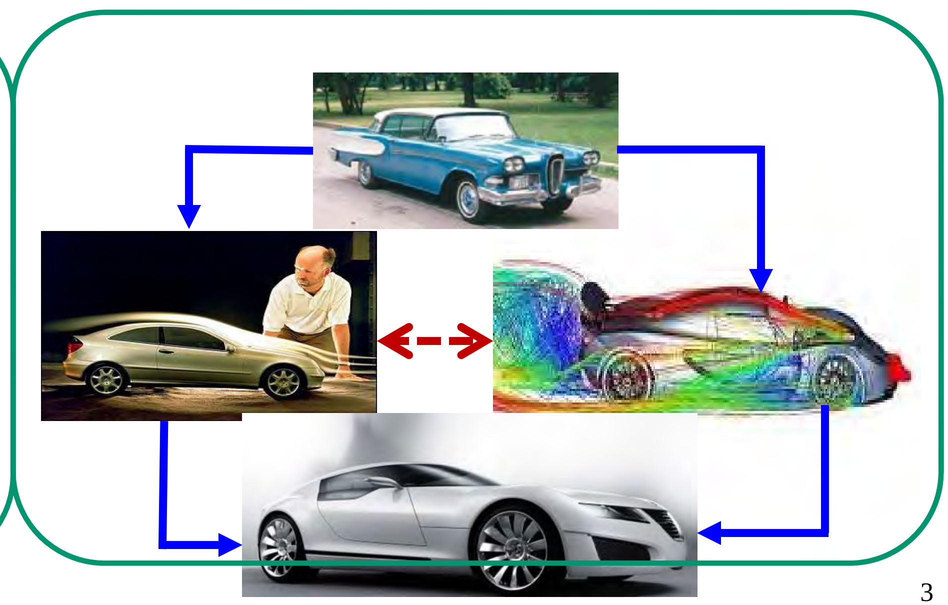
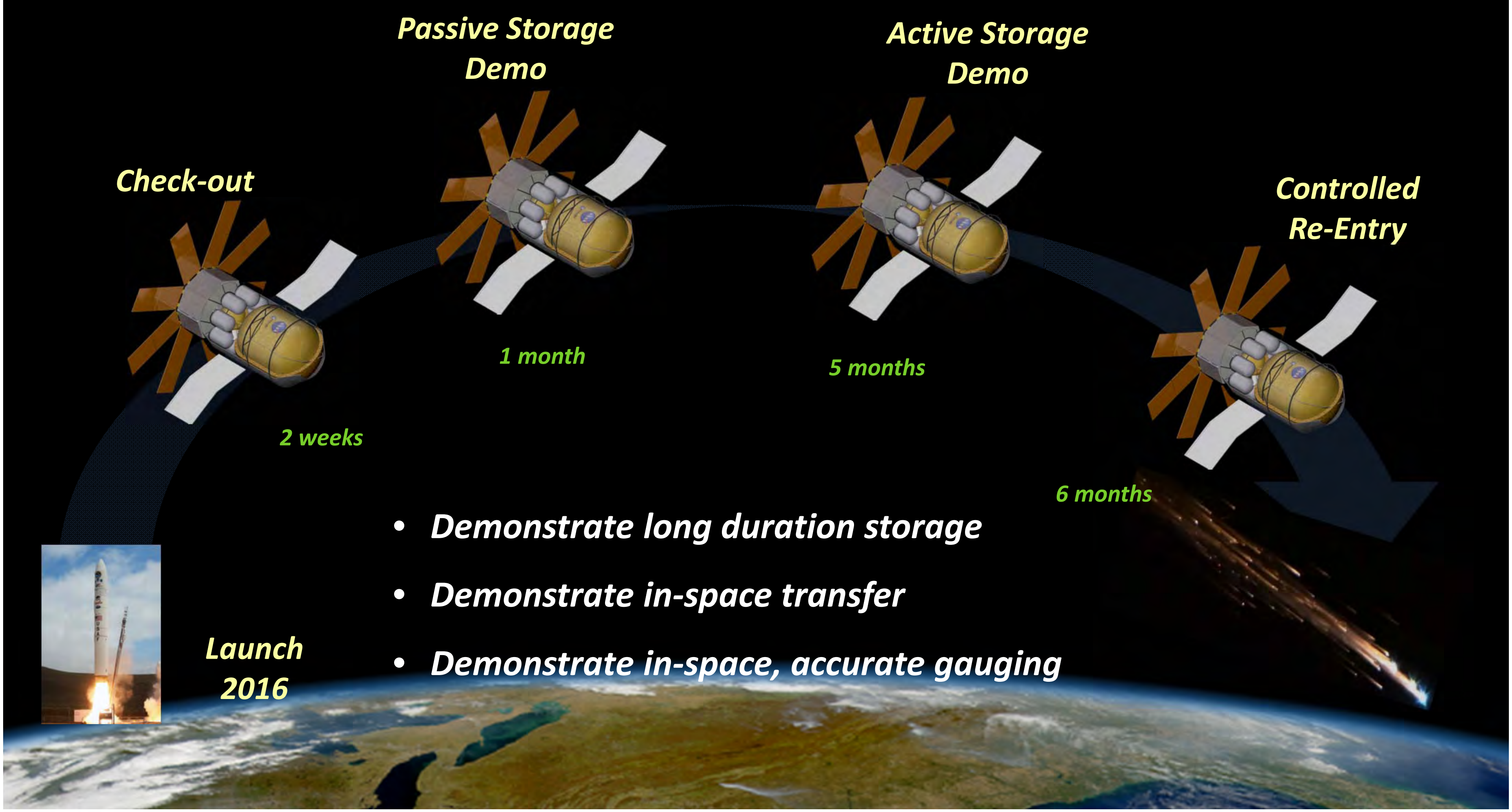
- Cryogenic Storage &Transfer are enabling propulsion technologies in the direct path of nearly all future human or robotic missions
- It is identified by NASA as an area with greatest potential for cost saving
- This proposal aims at resolving fundamental scientific issues behind the engineering development of the storage tanks
- We propose to use the ISS lab to generate & collect archival scientific data:
  - raise our current state-of-the-art understanding of transport and phase change issues affecting the storage tank cryogenic fluid management (CFM)
  - develop and validate state-of-the-art CFD models to innovate, optimize, and advance the future engineering designs





Related Mission: Cryogenic Propellant Storage and Transfer Technology Demonstration Mission

NASA is undertaking a demonstration mission to advance cryogenic propellant storage and transfer technologies that will enable exploration beyond Low-Earth Orbit



- *Demonstrate long duration storage*
- *Demonstrate in-space transfer*
- *Demonstrate in-space, accurate gauging*

Broad Scientific Goals of ZBOT

- Perform hand-in-hand experimentation, theoretical analysis, and computational modeling to:
  1. Gain a fundamental understanding of the phase change and transport phenomena associated with tank pressurization and pressure control
  2. Determine the time constants associated with pressurization, mixing, destratification, and pressure reduction for different gravitational environments
  3. Determine the effects of noncondensables on evaporation and condensation and transport phenomena
  4. Delineate the different microgravity transport/phase change mechanisms associated with different mixing/cooling strategies
  5. Investigate the nature of microgravity superheating and its effect on boil-off
  6. Validate and verify a state-of-the-art two-phase CFD model for cryogenic storage
- Produce archival data and simulations that will not only benefit the cryogenic storage tank design but a multitude of other two-phase flow operations and processes in space

ZBOT-1	ZBOT-2	ZBOT-3
Fluid Mixing	NonCondensable	Active Cooling

ZBOT-1 Engineering Questions: Pressurization & Pressure Control

- How much natural mixing will take place in a given tank during operation at various gravitational levels?
- How much forced mixing is needed to thermally de-stratify the tanks without active cooling?
- Under what conditions will it be necessary to augment the thermal destratification through active cooling?
- How effectively do mixing-only and/or mixing-with-active-cooling decrease the pressure reduction times?

Need: reliable engineering correlations for mixing, destratification, and pressure reduction times as functions of relevant tank parameters such as heat leak rates, mixing flow rates, and fill levels

Application: sizing of the pumps, determining forced mixing modes, possible placement of flow control structures, and sizing and implementation of the active cooling mechanisms (TVS, Cryocooler, etc.)

Important Experimental Components & Science Requirements

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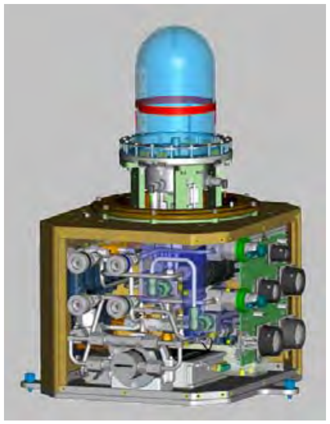

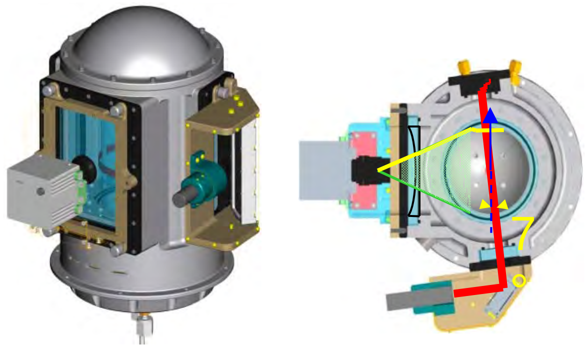

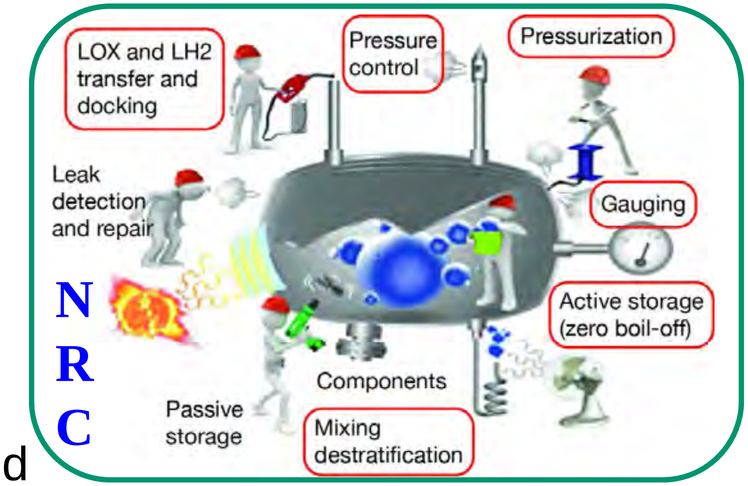

ZBOTComponents

- ventless Dewar(s)
- temp-controlled shield
- fluid support unit
- axial mixing jet
- longitudinal spray bar
- noncondensable gas injection
- Liquid Acquisition Devices (LADs)

ZBOT Requirements:

- transparent Dewar & fluid
- tightly controlled thermal & flow BC s
- accurate & local temperature measurement
- in-flight fluid degassing
- accurate determination of ullage pressure and gaseous concentration
- whole-field visualization of interface, flow. and velocimetry using PIV.

Main CPST Elements:

- Broad Area Cooling (BAC)
- active internal cooling
- dynamic mixing
- noncondensable effects
- liquid transfer
- mass gauging
- LAD operations

Why Small-Scale Experiment Simulant Fluid?

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NRC Decadal Report:

- "1G empirically-based predictive methods in the design of the future multiphase technologies are of limited use "
- "a new predictive capability and design methodology needs to be adopted that relies in particular on physically-based multiphase models that quantify accurately the effects of gravity."
- "to be effective, such models must necessarily be assessed against, appropriate small scale reduced-g data, and they must be capable of accurately scaling-up these data to the large multiphase systems for NASA's future human exploration missions."

CPST: Validate the Technology - Demonstrates performance of the engineering components: cryocoolers, pump, radiation shield

ISS:
- Controllable BCs -accurate measurements
- Flow visualization & velocimetry
- Extensibility Gap in scale and fluid closed by the model

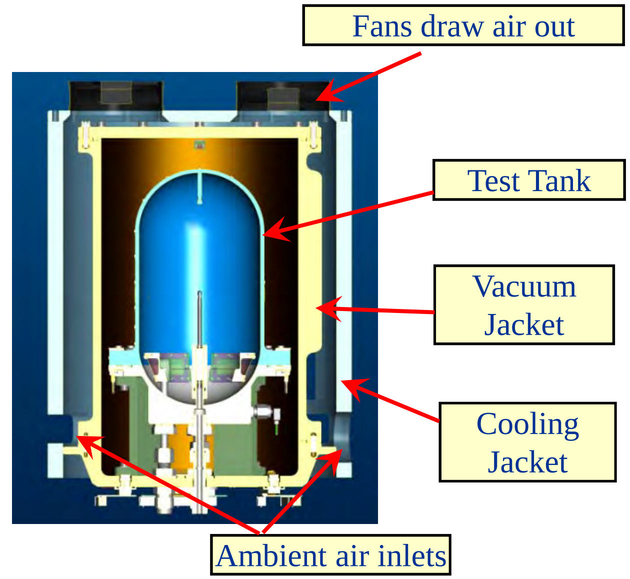
- **CPST extensibility gap:** 2 meter ➔ 8 meter LH2 ➔ LOX, Methane
- **Proposed ISS experiment will be able to bridge the CPST extensibility gaps with future mission applications**

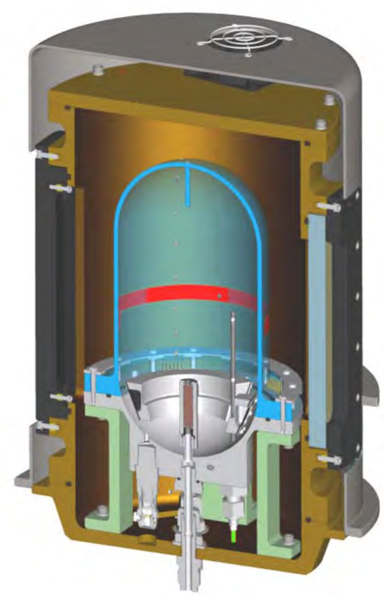
ZBOT-1 Experiment Description

- ZBOT-1 will involve both pressurization and pressure reduction tests
    - Pressurization tests will be conducted by direct heating of the tank wall
    - Pressure reduction tests will be accomplished through thermal destratification of the bulk liquid by forced jet mixing
- Parametric test runs will investigate the effect of the important system elements of a pressure control strategy on pressurization and pressure control:
    - Wall heat flux (heater)
    - Jet temperature
    - Jet flow rate
    - Tank fill level

Heat Leak

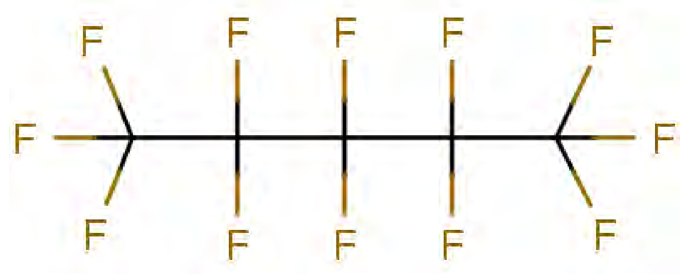
- During each test, pressure and temperature are locally measured and the velocity field and ullage location in the liquid are non-intrusively captured





Test Fluid

- Perfluoro-n-Pentane (PnP, or C_5F_{12})
- High purity (99.7% straight-chained n-isomer)
- Non-flammable, non-toxic, refrigerant/cleaning fluid
- Physical properties
  - Boiling Point = 29°C @ 1 atm
  - Vapor Pressure = 12.5 psia @ 25°C
- Benefits
  - Has the desired physical properties for science
  - Density matched with DPIV particles
  - Tox 0 – Approved by JSC toxicology and MSFC ECLSS groups



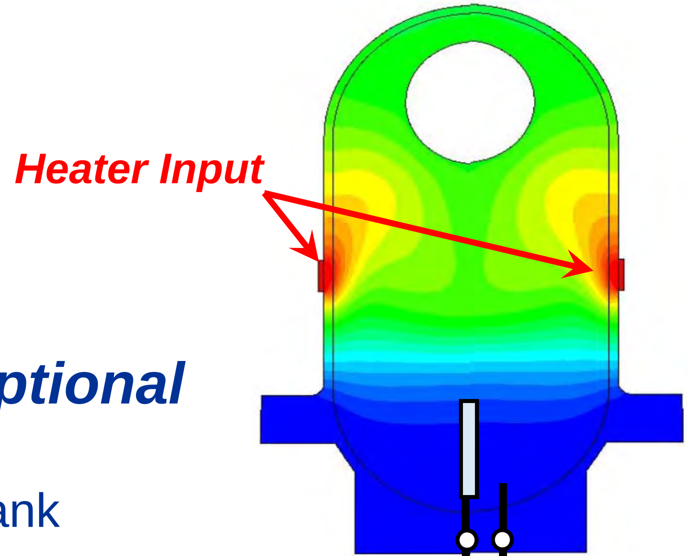
PnP n-Isomer (Straight Chained) Chemical Structure

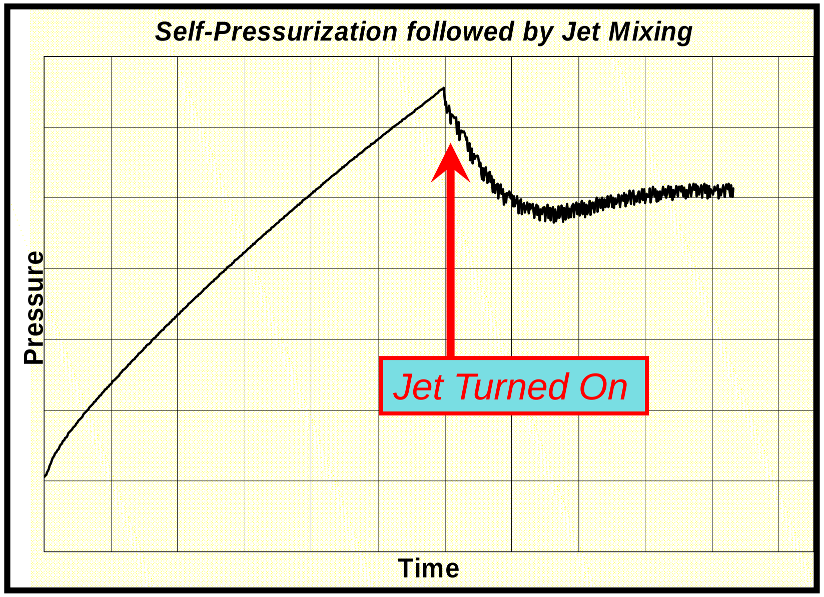
1. Self-Pressurization

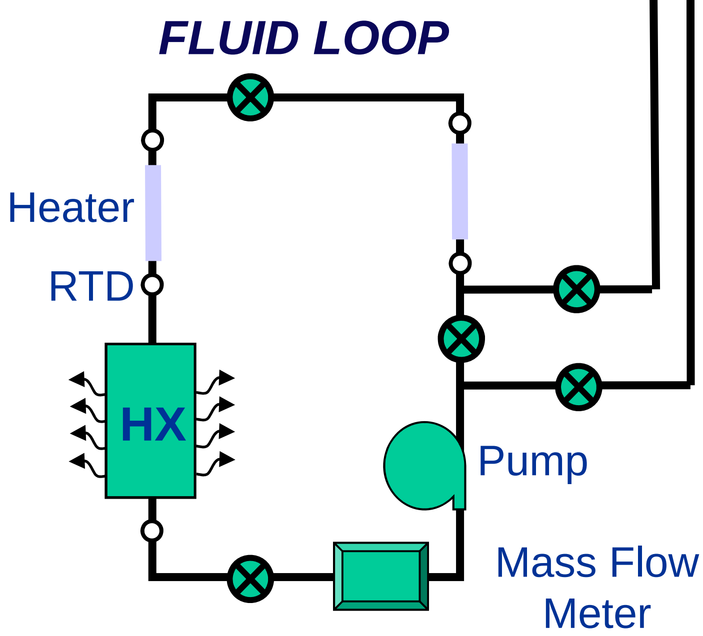
- Heat for 12 hours max.
- Heat at 0.5 to 1.0 Watts

2. Pressure Control via Mixing; Cooling Optional

- Mix with dQ/dT = 0 ***OR***
- Sub-cooled mixing used after test to rapidly cool tank





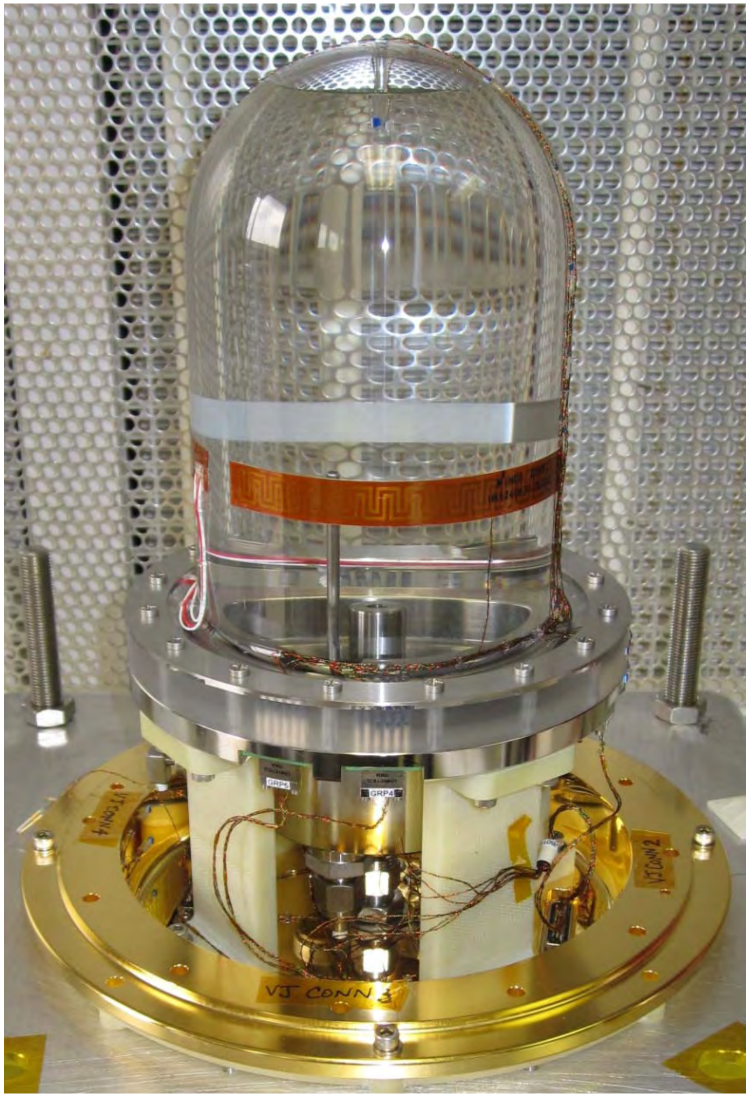


Boundary Conditions:

- Add precise heat to fluid using resistive heater strips
- Reduce heat losses through radiation, conduction, and convection
- Circulate temperature-controlled fluid

Instrumentation:

- RTDs measure temperature distributions to ±0.1 °C
- Pressure measured to ±0.05 psia
- Fluid velocity fields via Particle Imaging Velocimetry



Test Tank with Vacuum Jacket Removed and Base

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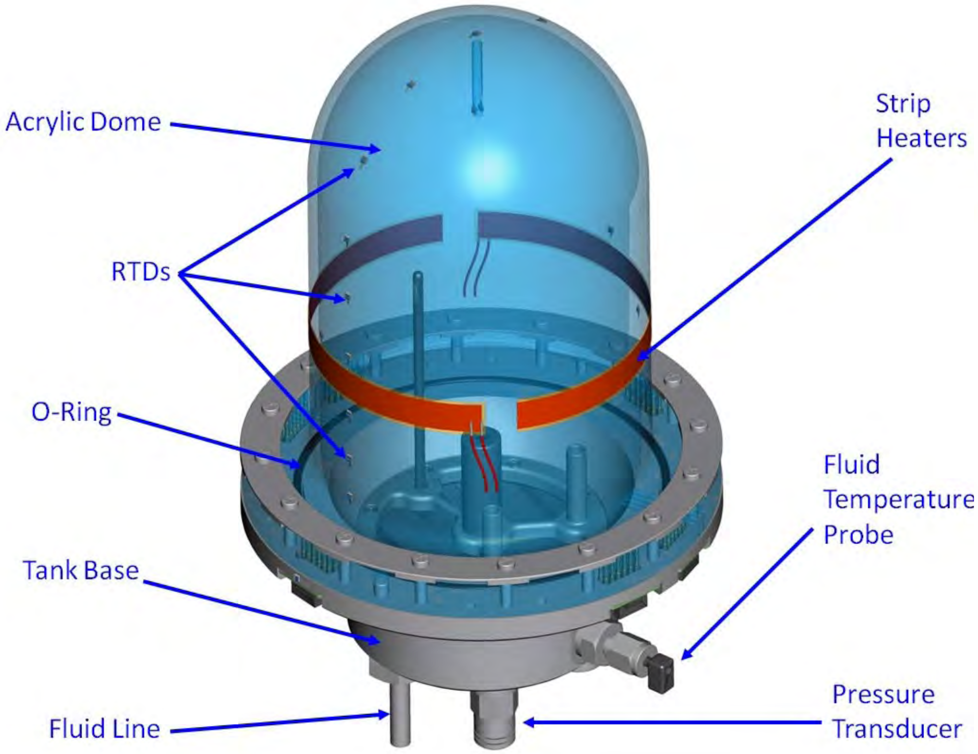
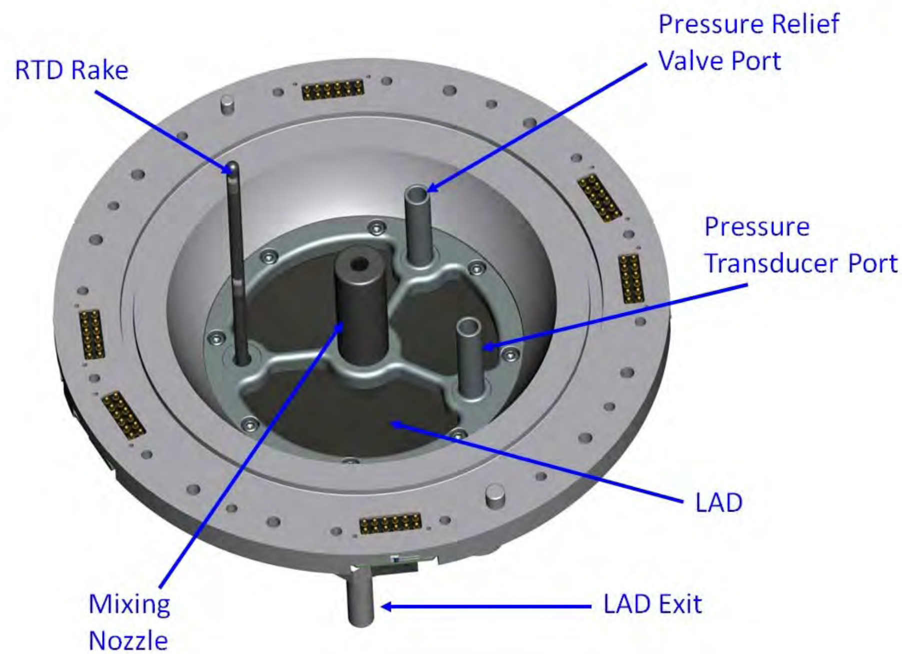
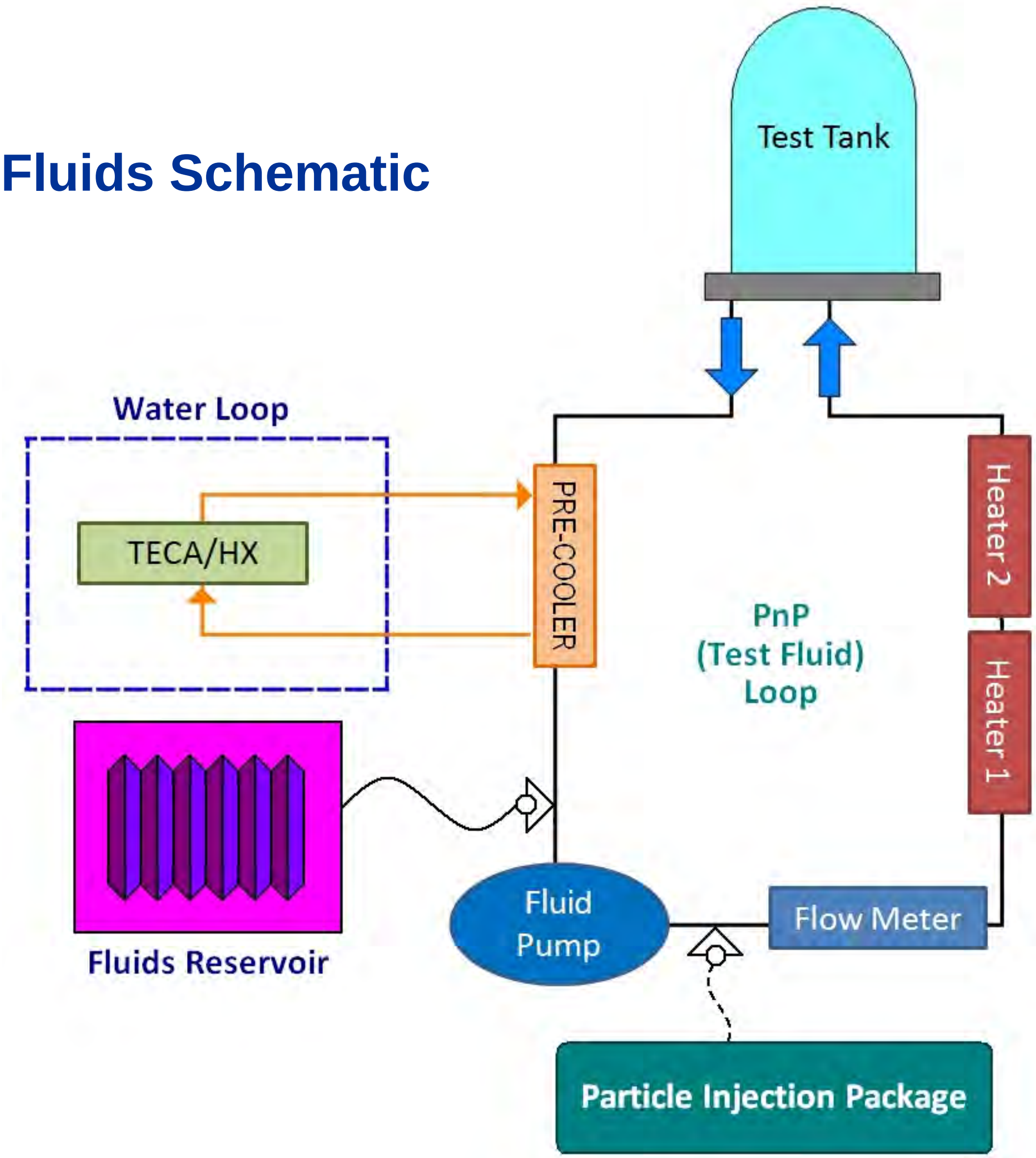
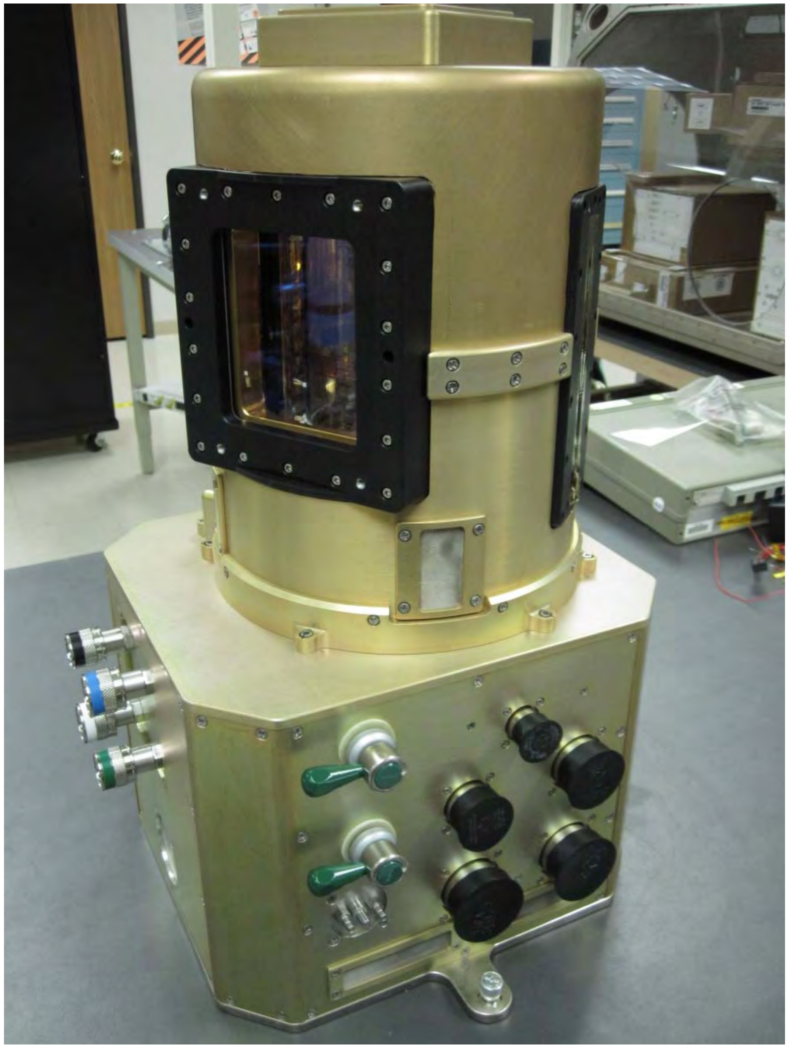




Simplified Fluids Schematic



ZBOT Test Section/FSU Engineering Model



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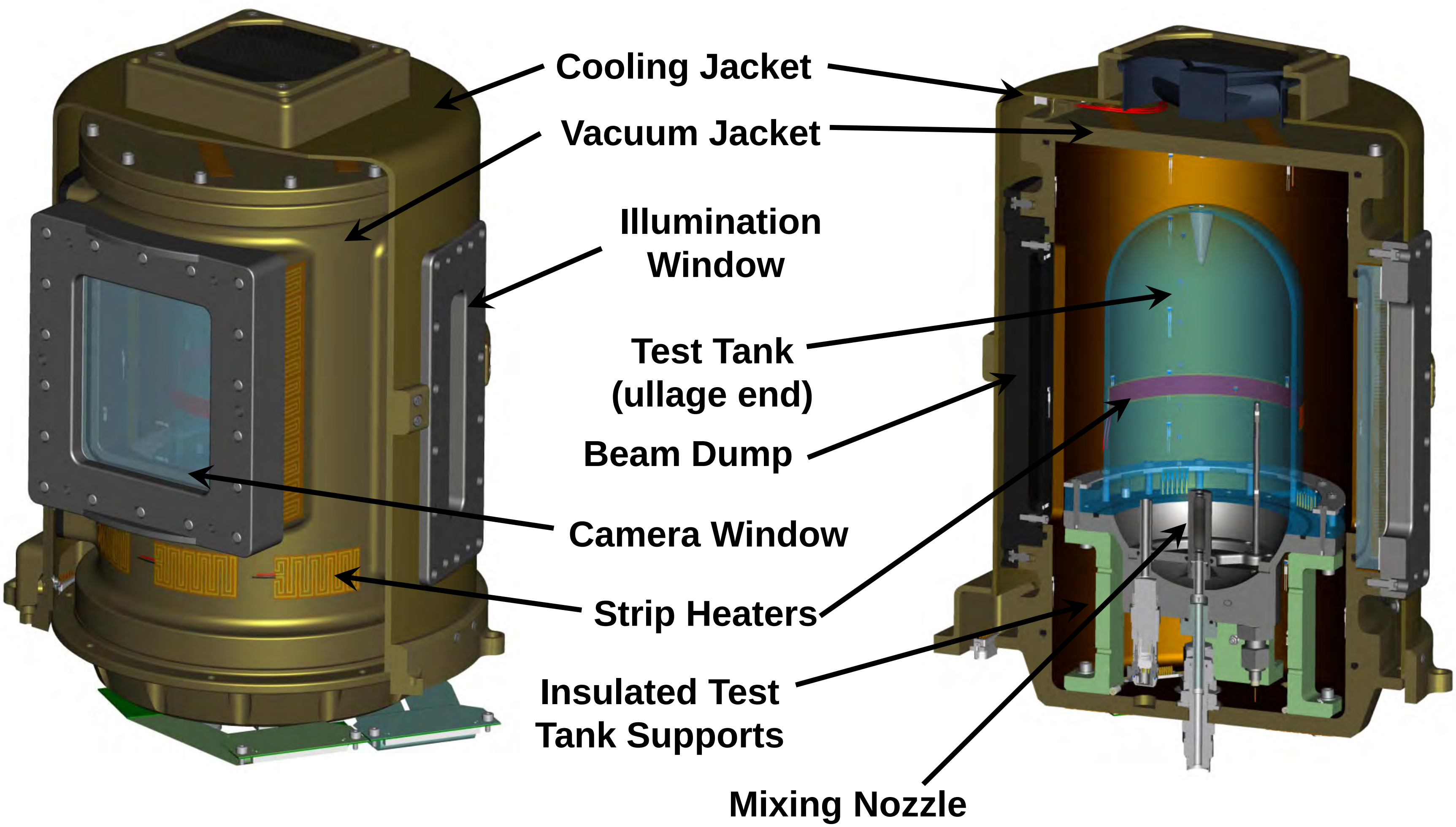
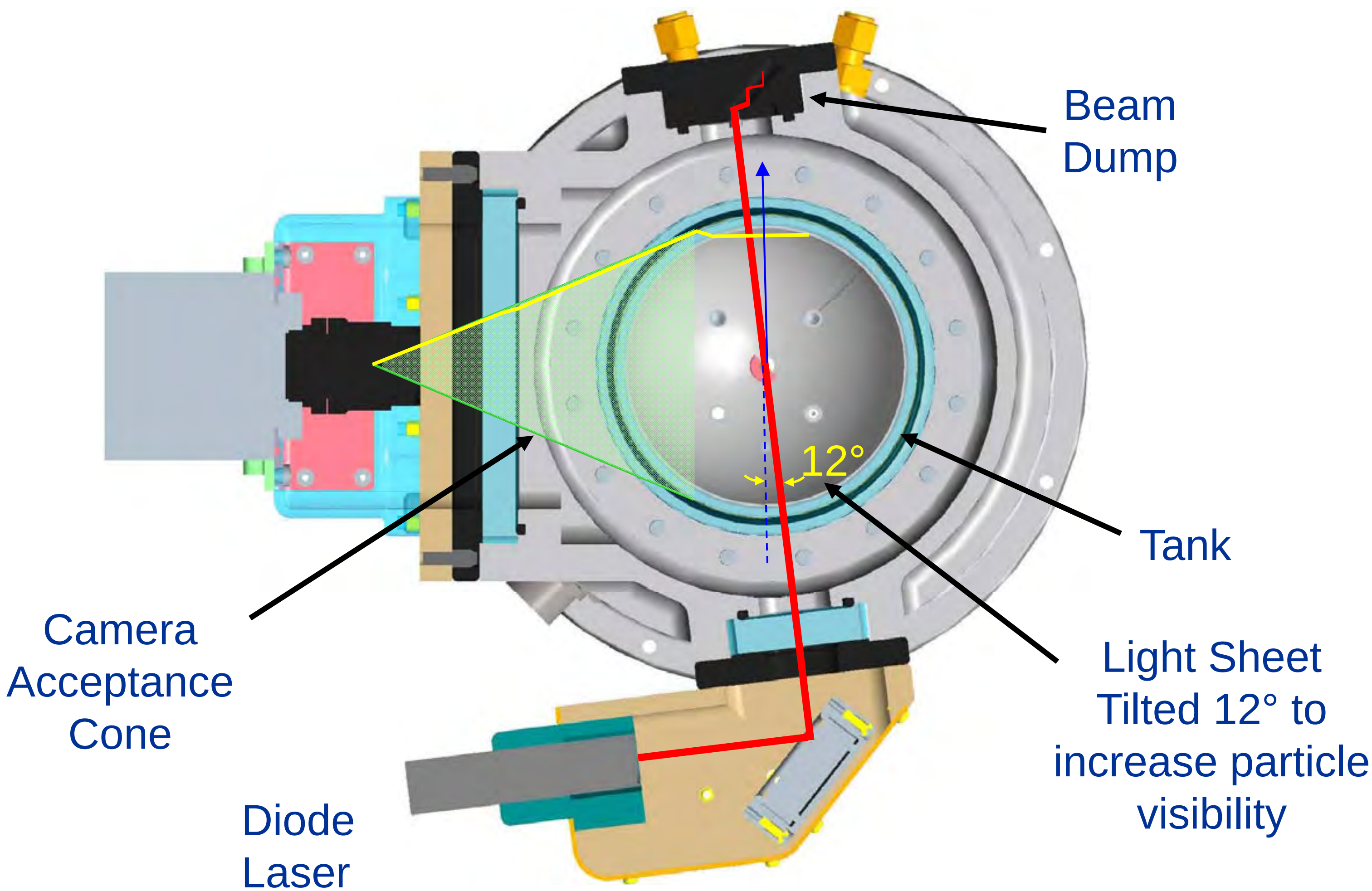
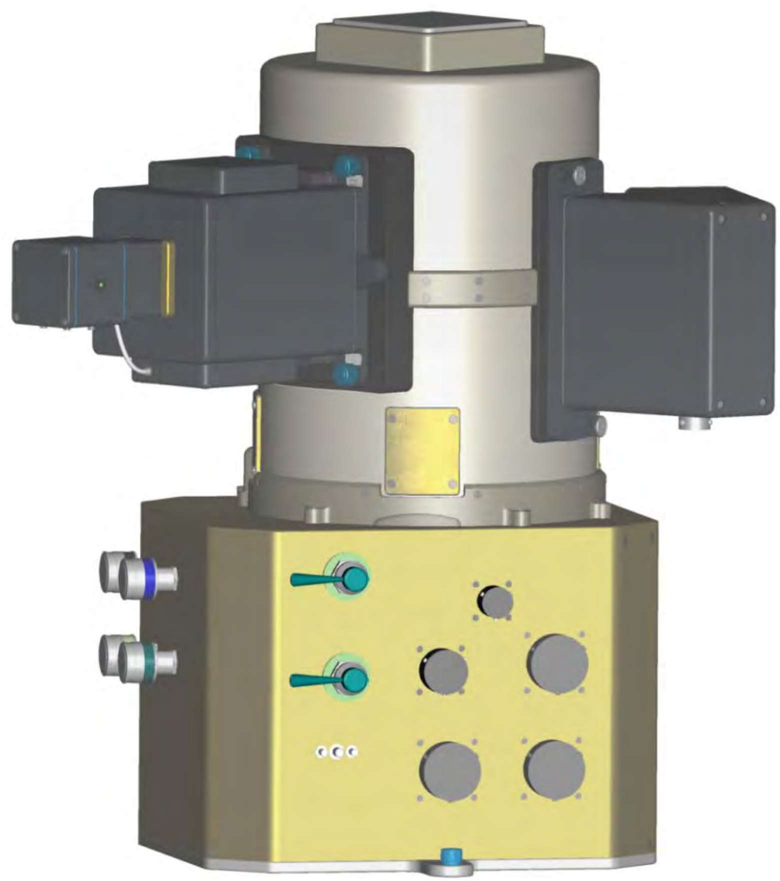
Test Section – Cross Section



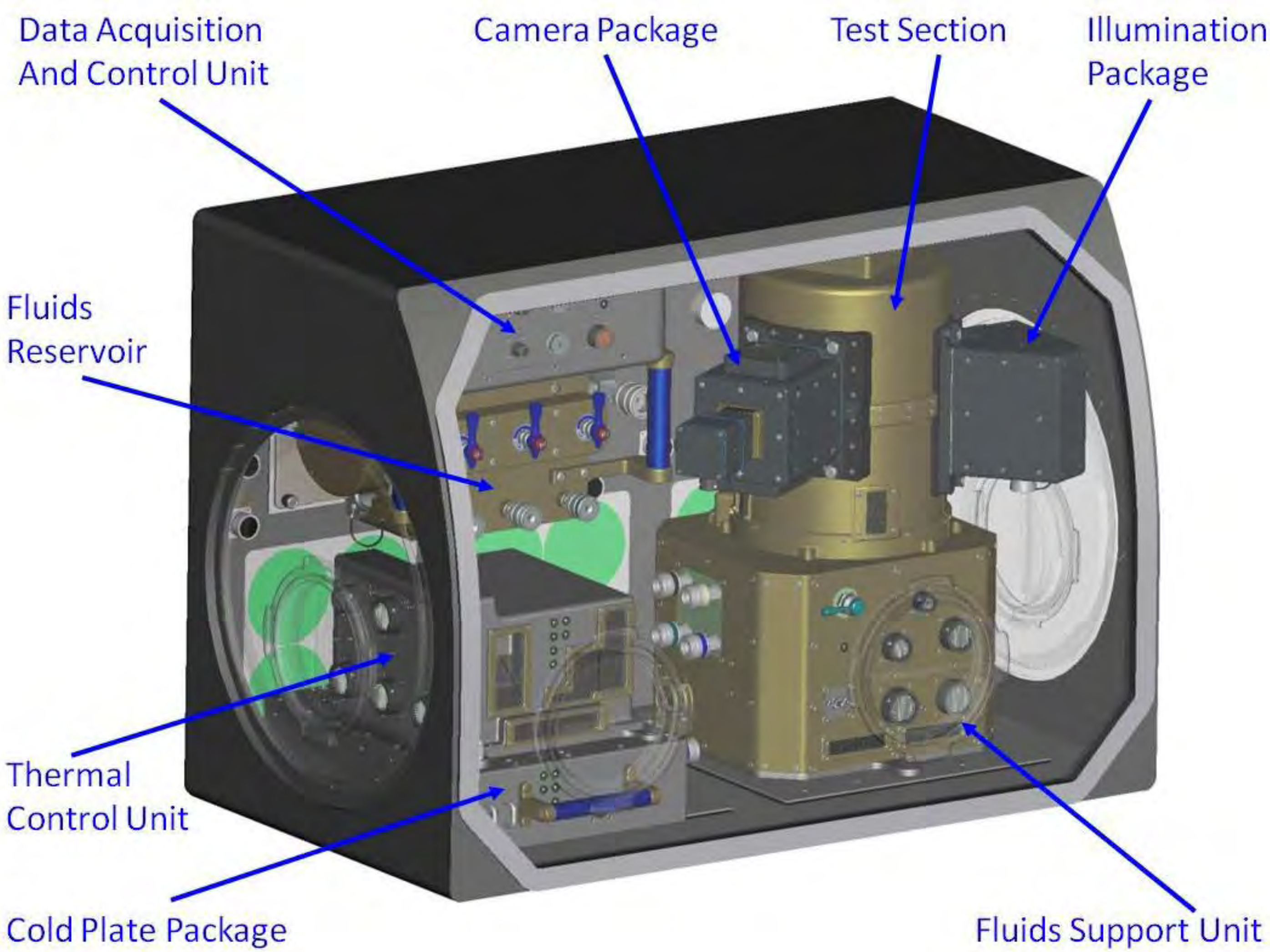
Optical System



Camera and Illumination Packages Mounted to the Test Section



ZBOT in the MSG Work Volume



Zero Boil-Off Tank Experiment-2 (ZBOT-2): Noncondensable Gas Effects

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PI: Dr. Mohammad Kassemi, NCSER/GRC
Co-I: Dr. David Chato, NASA GRC
PS: David Plachta , NASA GRC
PM: William Sheredy, NASA GRC
Engineering Team: ZIN Technologies, Inc.

Objective:

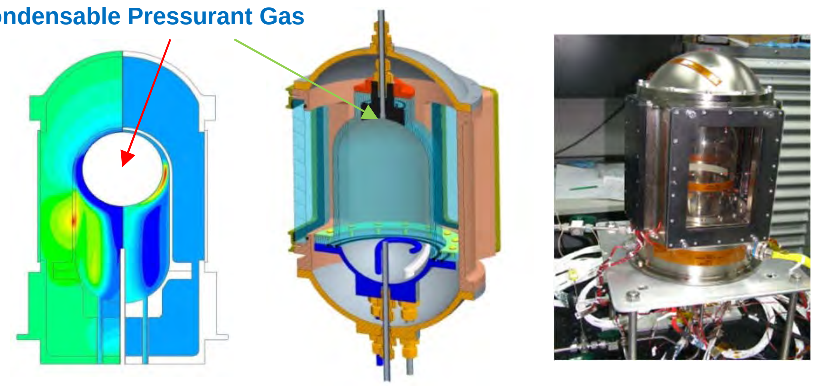
- Aid the design of NASA's space-based cryogenic storage systems by investigating the effects of noncondensable gases on tank pressure control
- Characterize and assess the effects of noncondensables on evaporation and condensation by obtaining microgravity two-phase flow and heat transfer data in a ventless Dewar
- Gather high quality microgravity data under controlled conditions for validation of storage tank CFD models and development of empirical engineering correlations

Relevance/Impact:

- ***Reduce launch mass*** (cost) by aiding the development of novel dynamic pressure control schemes for long-term storage of cryogenic fluids
- ***Decrease the risks*** of future space missions by clarifying and assessing the impact of noncondensables on storage tank pressure reduction/control
- ***Increase design reliability*** by providing archival data for benchmarking and improving CFD models used by the Cryogenic Fluids Management community and the Aerospace Companies for future (ground-tested-only) tank designs

Development Approach:

- Flight phase: ***Modify*** the ZBOT-1 experimental hardware and diagnostics for non-condensable gas studies; Obtain microgravity data to determine the effect of the noncondensable pressurant on tank pressurization, thermal destratification, and pressure reduction through mixing in microgravity
- Modeling: ***Expand*** the ZBOT-1 two-phase CFD model to incorporate the non-condensable gas effects
- Validation: Validate the noncondensable tank models with microgravity data
- Scale-up: Use the validated CFD models and empirical microgravity correlations to scale-up the design of the future tanks and dynamic pressure control system



Hand-in-Hand Microgravity & 1G Experimentation and Computational Modeling

ISS Resource Requirements

Accommodation (carrier)	Fluids Integrated Rack
Upmass (kg) (w/o packing factor)	80 - 100 kg
Volume (m^3) (w/o packing factor)	0.10 - 0.12 m^3
Power (kw) (peak)	0.100 kW
Crew Time (hrs) (installation/operations)	15 - 20 hrs. total
Launch/Increment	TBD

Zero Boil-Off Tank Experiment-3 (ZBOT-3): Active Cooling

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ZIN Technologies

Glenn Research Center

PI: Dr. Mohammad Kassemi, NCSER/GRC
Co-I: Dr. David Chato, NASA GRC
PS: David Plachta , NASA GRC
PM: William Sheredy, NASA GRC
Engineering Team: ZIN Technologies, Inc.

Objective:

Aid design of NASA's cryogenic storage systems by studying ***different active cooling strategies*** for future Zero-Boil-Off (ZBO) tank pressure control designs:

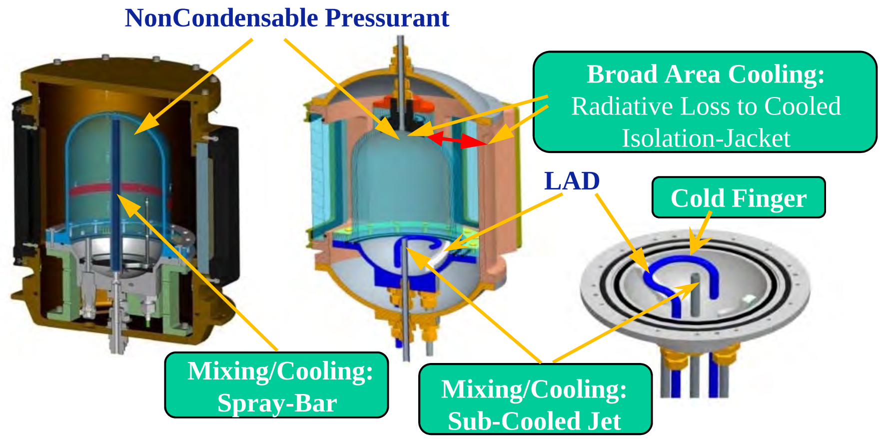
- Obtain microgravity flow and heat transfer data to characterize tank thermal destratification and pressure reduction for: (i) sub-cooled jet mixing (ii) spray-bar mixing; and (iii) broad area cooling with intermittent mixing
- Provide high quality microgravity data under controlled conditions for development, validation and verification of tank pressure control models, CFD codes, and empirically-based correlations
- Perform a quantitative comparison among different ZBO active pressure control strategies using microgravity data and model simulations

Relevance/Impact:

- **Reduce launch mass** (cost) by aiding development of novel *active cooling ZBO pressure control* schemes for long-term storage of cryogenic fluids
- ***Reduce the risks*** of future missions by testing pressure control systems never tested in microgravity and ***increase design reliability*** by providing archival data for benchmarking and improving CFD models/codes used by the Cryogenic Fluids Management Community (CFM) and the Aerospace Companies for future (ground-tested-only) tank designs

Development Approach:

- Flight phase: ***Modify*** the ZBOT-2 experimental apparatus to accommodate the pressure control components needed for active cooling studies
- Modeling: ***Expand*** the ZBOT-2 two-phase CFD model to incorporate the active cooling components
- Validation: Validate the active cooling tank models with microgravity data
- Scale-up: Use the validated CFD models and empirical microgravity correlations to scale-up the design of the future tanks and their active cooling ZBO pressure control system



ISS Resource Requirements

Accommodation (carrier)	Fluids Integrated Rack
Upmass (kg) (w/o packing factor)	80 - 100 kg
Volume (m^3) (w/o packing factor)	0.10 - 0.12 m^3
Power (kw) (peak)	0.100 kW
Crew Time (hrs) (installation/operations)	15 - 20 hrs. total
Launch/Increment	TBD

ZBOT STATUS

- **ZBOT CDR** under way, Formal Review Scheduled for December 10, 2012
- **ZBOT Hardware** complete planned for December 2013
- **ZBOT flight hardware availability** planned for August 2014
- **ZBOT 2,3** still pre-phase A

Summary

- **ZBOT** ready to go soon!
- **ZBOT** provides valuable data for understanding Cryogenic Propellant Storage and Transfer:
  - Observation of tank fluid mixing in low gravity with condensing fluid
  - Accurate control of thermal environment with precise temperature measurement and control
  - Accurate measurement of fluid motion with laser Particle Imaging Velocimetry
- **ZBOT flight experiment** data will significantly improve the modeling of Cryogenic Propellant Storage and Transfer
- **ZBOT test hardware** extensible to several additional Cryogenic Propellant Storage and Transfer research efforts